Boosting SUSY

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Content

- Hadronic objects.
  - Boosted massive SM particles from SUSY decays.
  - SUSY resonances.
- Leptonic & mixed objects.

Boosted SM particles from SUSY decays

- R-parity   no SUSY resonance decays to SM particles.
- Produce massive SM particles (W,Z,h,t) in SUSY decays.
  - Potentially with large boost due to SUSY mass differences.
- Work on some topics started:
  - SUSY cascade decays.
    [Butterworth, Ellis, ARR, hep-ph/0702150]
  - Potential for MSSM Higgs discovery in SUSY events.
    [Kribs, Martin, Roy, Spannowsky, arXiv:0912.4731,1006.1656]
  - Reconstructing top from stop decays
    [Plehn, Spannowsky, Takeuchi, Zerwas, arXiv:1006.2833]

SUSY cascade decays

- We know how to do long cascade decays with «clean» leptons at the LHC using **edge measurements**, *e.g.*

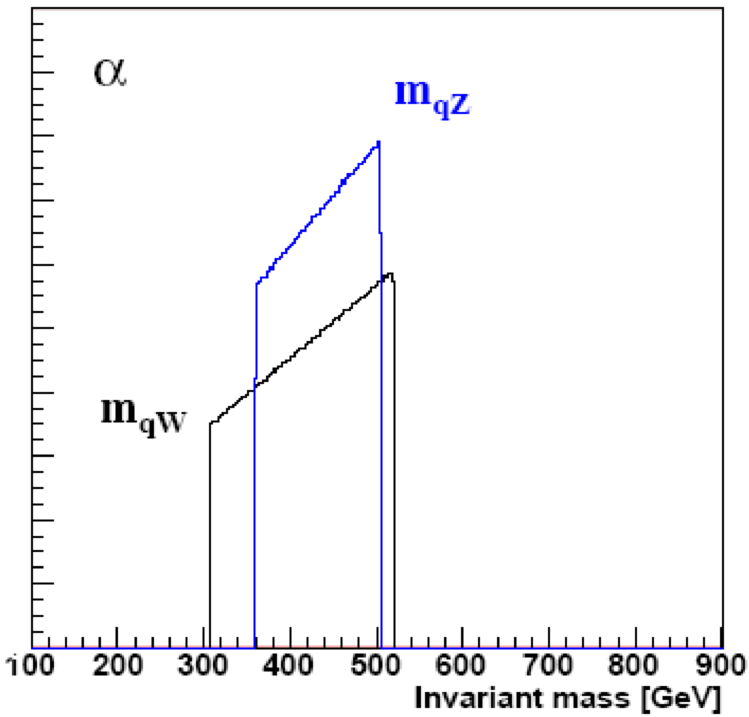
$$\tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow q l^{\pm} \tilde{l}^{\mp} \rightarrow q l^{\pm} l^{\mp} \tilde{\chi}_1^0$$

- What about gaugino decays to SM bosons in SUSY?

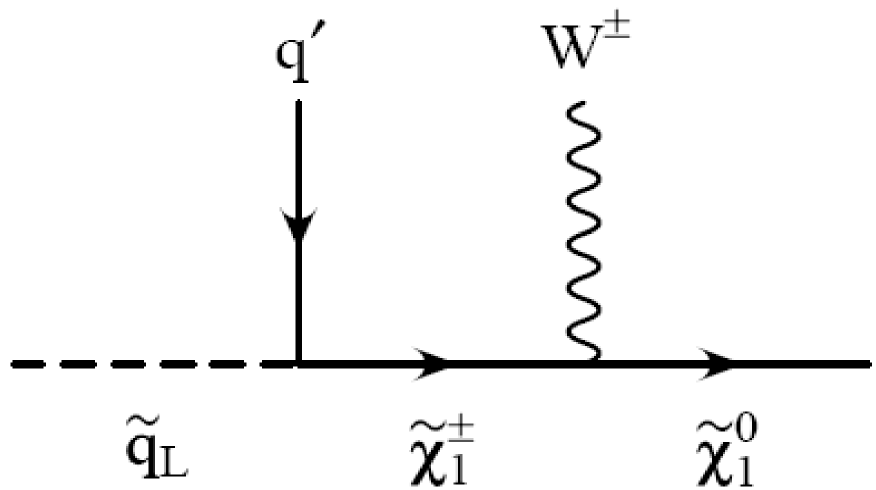
$$\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} \tilde{\chi}_1^0, \quad \tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0, \quad \tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$$

The only decay that works well with leptons is $Z \rightarrow l^+ l^-$
What about $W \rightarrow q q'$ or $h \rightarrow b \bar{b}$?

SUSY cascade decays

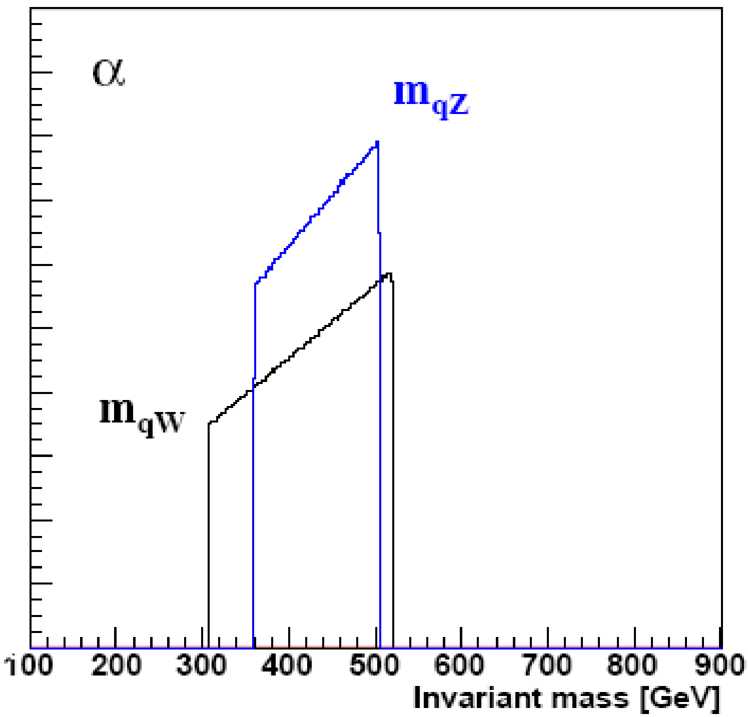


Edge measurements can be used as in «standard» decay chains, taking care to include SM masses:



[Butterworth, Ellis, ARR, hep-ph/0702150]

SUSY cascade decays



Edge measurements can be used as in «standard» decay chains, taking care to include SM masses:

$$\left(m_{qZ}^{\mathrm{ext}}\right)^2 = m_Z^2 + \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)}{m_{\tilde{\chi}_2^0}}\left(E_Z \pm p_Z\right)$$

$$p_Z^2 = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2 - m_Z^2)^2 - 4\mathrm{m}_Z^2 m_{\tilde{\chi}_1^0}^2}{4\mathrm{m}_{\tilde{\chi}_2^0}^2}$$

[Butterworth, Ellis, ARR, hep-ph/0702150]

Cascade decays: but why do we care?

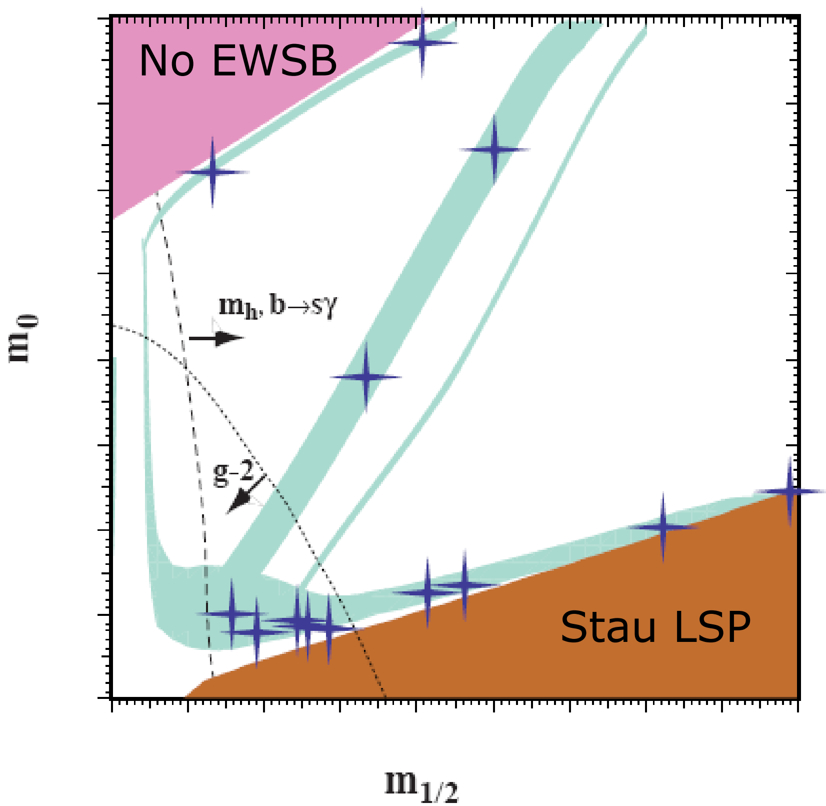


Illustration of CMSSM/mSUGRA for generic values of

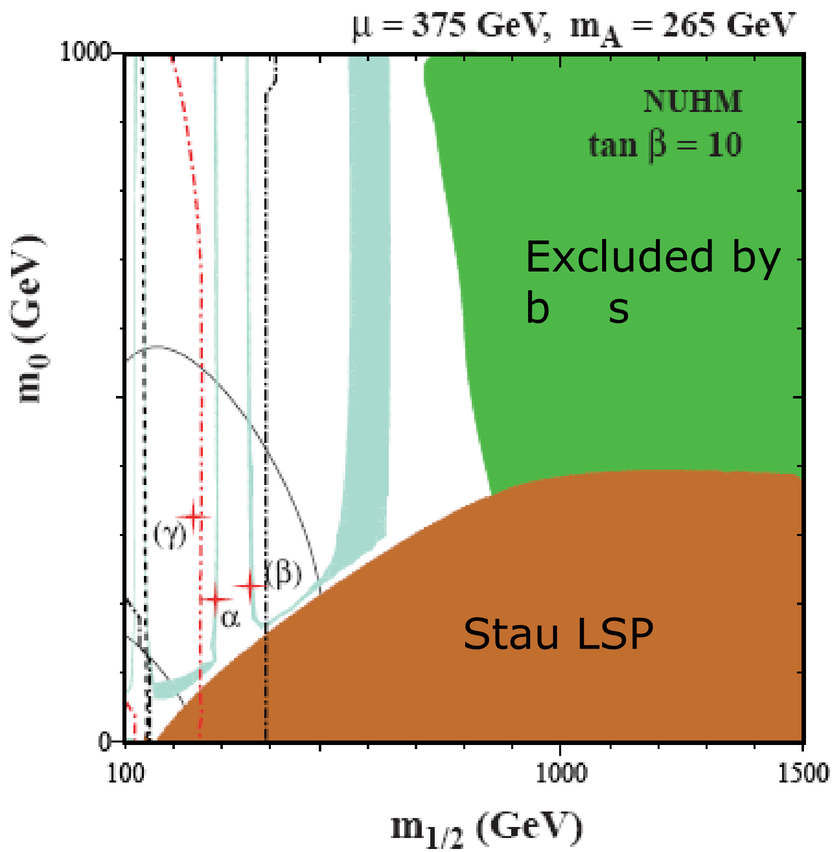
$$A_0,\ \tan\beta,\ \mathrm{sgn}\,\mu$$

Very limited production of massive SM bosons (W,Z,h) in DM allowed regions.

Small relaxation of unification assumptions can give larger BRs.

[Battaglia *et al.*, hep-ph/0106204]

Cascade decays: but why do we care?



Non-Universal Higgs Mass (NUHM) and Gravitino Dark Matter (GDM) scenarios change DM allowed regions.

Point/BR	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm$
α	98.6	0.0	99.6
β	7.5	64.5	79.0
γ	0.0	0.0	99.9
δ	5.4	92.0	97.5

[De Roeck *et al.*, hep-ph/0508198]

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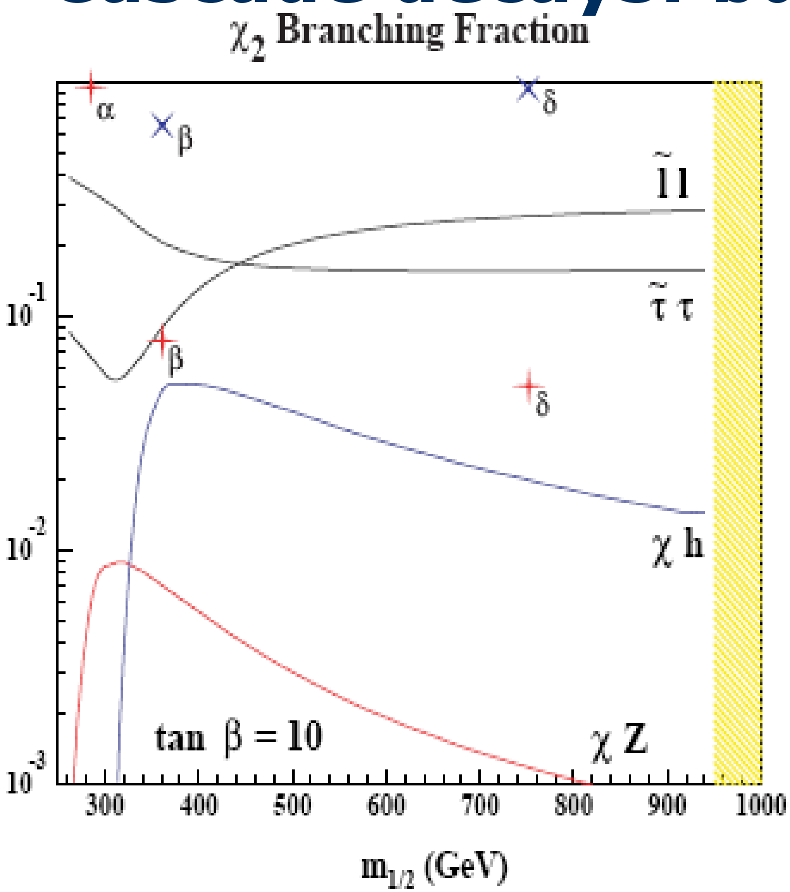

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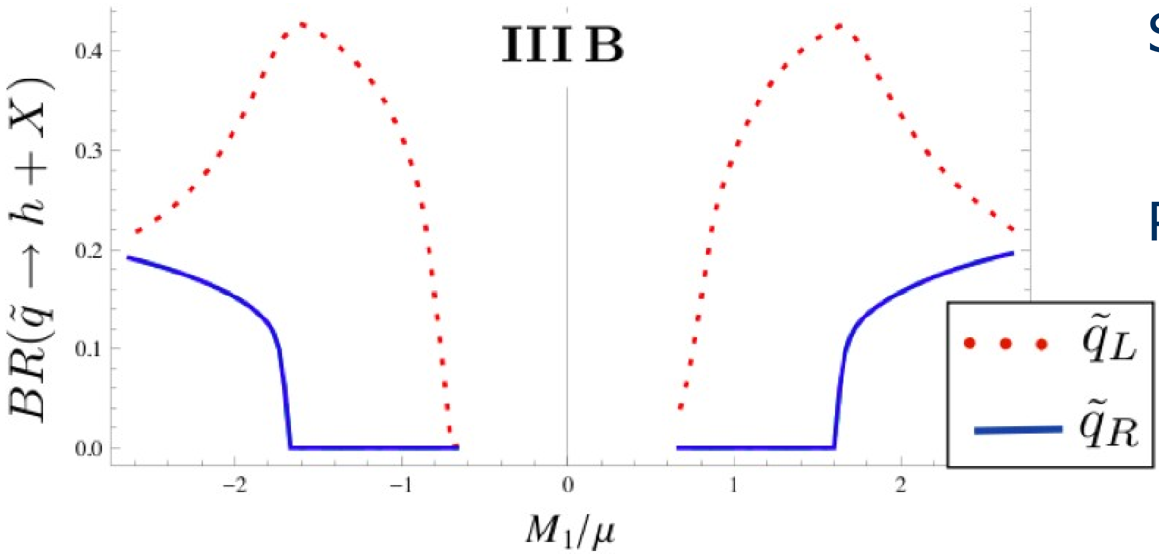
Aside: finding the MSSM Higgs(es)



Small μ leads to

$$\tilde{W}\,,\ \tilde{B} \to h\ /\ A\ /\ H + \tilde{H}$$

Plot shown for:

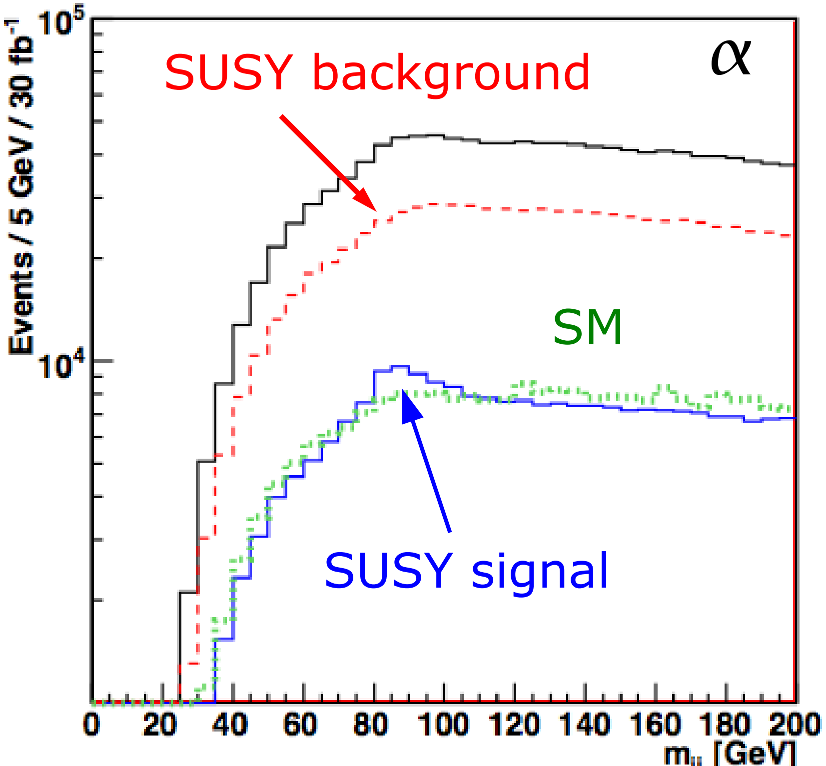
$$m_{\tilde{q}} = 1\,\mathrm{TeV}$$
$$m_{\tilde{l}} = 500\ \mathrm{GeV}$$
$$|\mu| = 150\ \mathrm{GeV}$$
$$M_2 = 2\,M_1$$

Large $\mathrm{BR}\,(h\,,A\,,H \to b\bar{b})$ generic in the MSSM.

For analysis details & results, see talk by Martin.

[Kribs, Martin, Roy, Spannowsky, arXiv:0912.4731,1006.1656]

Cascade decays: a whole lotta hadrons



MC study using ALPGEN/Herwig6.510/JIMMY for multiple jet backgrounds.

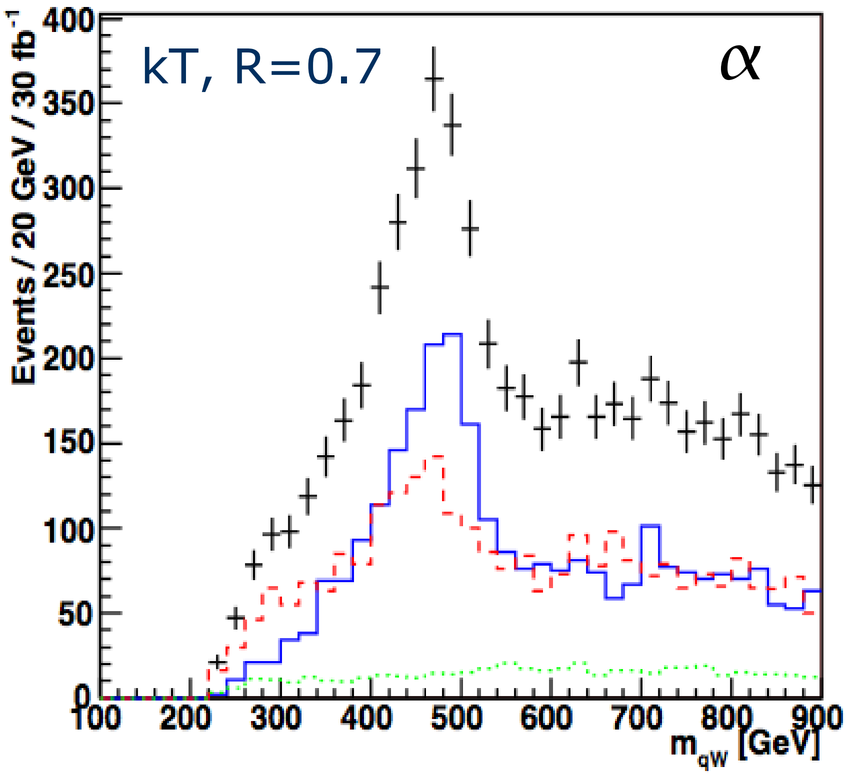
Looking for Ws in

$$\tilde{q}_L \to q' \tilde{\chi}_1^{\pm} \to q' W^{\pm} \tilde{\chi}_1^0$$

with di-jet invariant mass after 300 GeV cut on ETmiss.

[Butterworth, Ellis, ARR, hep-ph/0702150]

Cascade decays: with di-jet substructure



SM rejection cuts:

$$p_T^{\text{jet}} \geqslant 200,\ 200,\ 150\ \text{GeV}$$

$$E_T^{\text{miss}} \geqslant 300\ \text{GeV}$$

W candidate jet cuts:

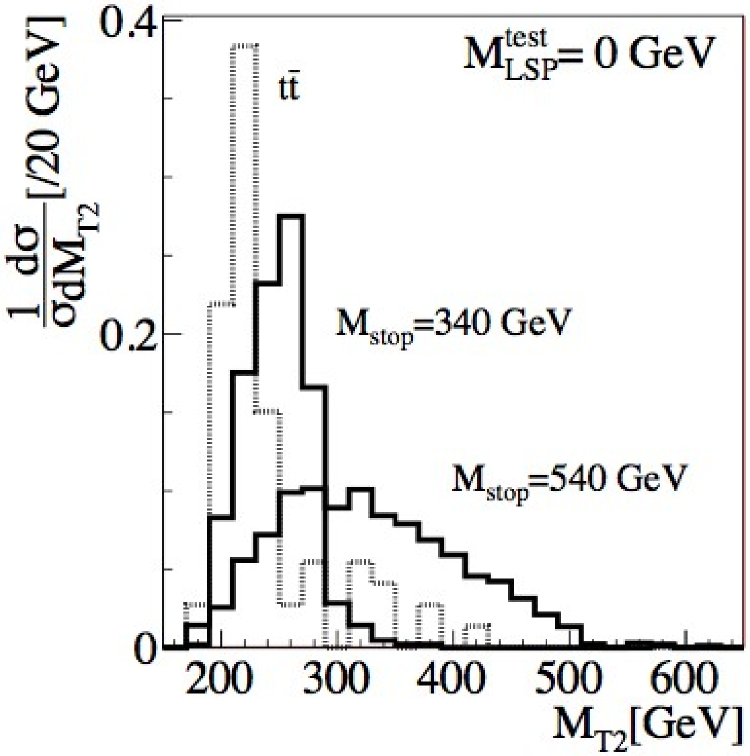
$$75\ \text{GeV} < m_j < 105\ \text{GeV}$$

$$1.5 < \log_{10}(\sqrt{d_{kl}^{(1)}}) < 1.9$$

kT distance

[Butterworth, Ellis, ARR, hep-ph/0702150]

Cascade decays: top quarks from stops



Potential large cross section for

$$pp \to \tilde{t}_1 \tilde{t}_1^* \to t\,\bar{t}\,\tilde{\chi}_1^0 \tilde{\chi}_1^0$$

given $m_{\tilde{t}_1} > m_t + m_{\tilde{\chi}_1^0}$ or even

$$pp \to \tilde{g}\,\tilde{g} \to t\,\bar{t}\,\tilde{t}_1 \tilde{t}_1^*, t\,t\,\tilde{t}_1^* \tilde{t}_1^*, \bar{t}\,\bar{t}\,\tilde{t}_1 \tilde{t}_1$$

Accurate reconstruction of top momentum of vital importance.

For analysis details & results, see talk by Takeuchi.

[Plehn, Spannowsky, Takeuchi, Zerwas, arXiv:1006.2833]

RPV decays of SUSY resonances

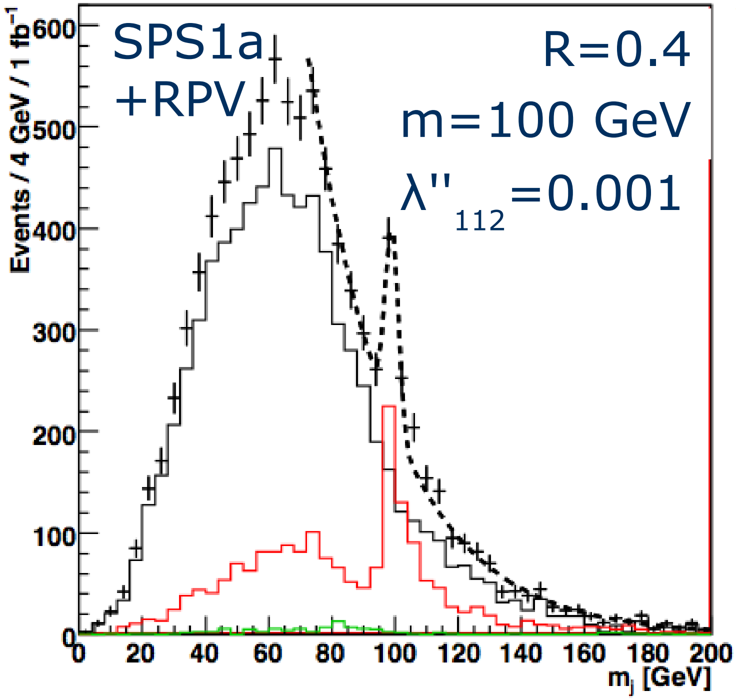
- With R-parity violation the (N)LSP can decay promptly into 2-4 quarks ($10^{-6} < \lambda < 10^{-2}$) via

$$W_{\mathrm{RPV}} \sim \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- The decay $\tilde{\chi}_1^0 \to qqq$ is notoriously difficult to reconstruct unless there are heavy flavours present.
- 20 possible combinations for 6 jets!
- Marginally doable if additonal leptons are present in the decay chain, but this is model dependent!

[Allanach *et al.*, hep-ph/0102173]

RPV decays: attempt with kT algorithm



Define a substructure y-cut that is not so mass-scale dependent:

$$y_1 = \min(p_{Tk}^2, p_{Tl}^2)/m_j^2 \times \Delta R_{kl}^2$$

Analysis requires two **neutralino candidate** jets. Clear resonance peak on exponential background.

ATLAS full detector simulation with k_T algorithm @ 10 TeV encouraging.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]
[French *et al.*, ATL-PHYS-PUB-2009-076]

RPV decays: now with C/A algorithm

With Cambridge/Aachen there is no p_T ordering of clusters. We pick significant clusterings by requiring:

$$z_{kl} = \frac{\min(p_{Tk}, p_{Tl})}{p_{Tk} + p_{Tl}} > z_{cut}$$

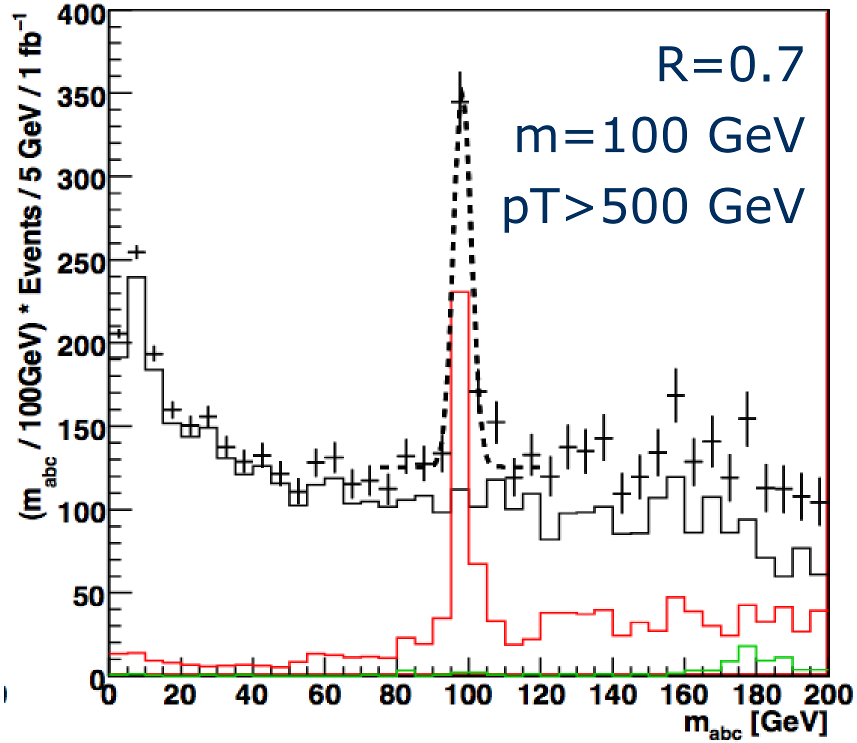
One can show that for QCD jets, when $\epsilon < m_j < R p_T z_{\rm cut}^{1/2}$,

$$m_j \frac{dn}{dm_j} \propto \frac{2C_F}{\pi}\left(\ln\frac{1}{z_{cut}} - \frac{3}{4}\right)$$

Order such clusterings by JADE distance $d_{kl} = p_{Tk}\, p_{Tl}\, \Delta R_{kl}^2$.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

RPV decays: now with C/A algorithm



Inclusive analysis picking one very hard jet with two mergers that have $z_{cut} > 0.15$.

Require the two mergers to have a significant mass ratio $\mu > 0.25$.

Combining neutralino candidate with extra hard jet gives squark mass estimate.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

Lepton jets

- SUSY with benefits
  - Non-minimal field content: extra U(1)'s & more complicated stuff.
  - NMSSM singlino: $\tilde{\chi}_2^0 \to l^+ l^- \tilde{S}$
  - GeV scale Dark Higgses and Dark gauge bosons:

$$\tilde{\chi}_{\mathrm{MSSM}} \to h_{\mathrm{dark}} / \gamma_{\mathrm{dark}} + \tilde{\chi}_{\mathrm{dark}}$$

[Arkani-Hamed, Weiner, arXiv:0810.0714]

- For more Dark Details, see Jay Wacker's talk later today.

Lepton jets & mixed

- With R-parity violation the (N)LSP can decay promptly into 2-4 leptons ($10^{-6} < \lambda < 10^{-2}$) via

$$W_{\mathrm{RPV}} \sim \lambda_{ijk} L_i L_j \bar{E}_k$$

- Expect neutrinos due to SU(2) structure.

NLSP	$LL\bar{E}$	$LQ\bar{D}$	$\bar{U}\bar{D}\bar{D}$
$\tilde{\chi}_1^0$	$\ell_i^\pm \ell_j^\mp \nu$	$q_j \bar{q}_k \ell^\pm (q_j \bar{q}_k \nu)$	$q_i q_j q_k (\bar{q}_i \bar{q}_j \bar{q}_k)$
$\tilde{\nu}$	$\ell_i^\pm \ell_j^\mp$ $\ell_i^\pm \ell_j^\mp \nu\nu$	$q_j \bar{q}_k$ $q_j \bar{q}_k \ell^\pm \nu (q_j \bar{q}_k \nu\nu)$	$\nu q_i q_j q_k (\nu \bar{q}_i \bar{q}_j \bar{q}_k)$
$\tilde{\tau}_R$	$\ell_i \nu$ $\ell_i^\pm \ell_j^\mp \nu\tau$	$q_j \bar{q}_k$ $q_j \bar{q}_k \ell^\pm \tau (q_j \bar{q}_k \nu\tau)$	$\tau q_i q_j q_k (\tau \bar{q}_i \bar{q}_j \bar{q}_k)$

Lepton-jet mixture quite generic with RPV.

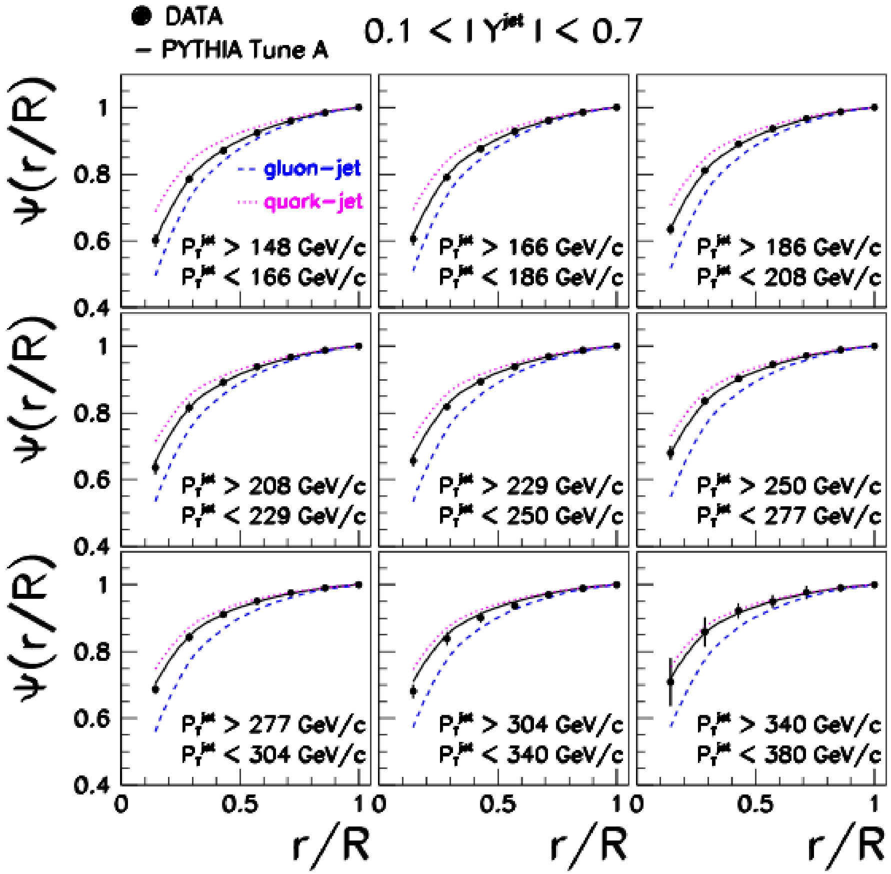
[Bomark, Lola, Osland, ARR, arXiv:0811.2969]

Conclusions

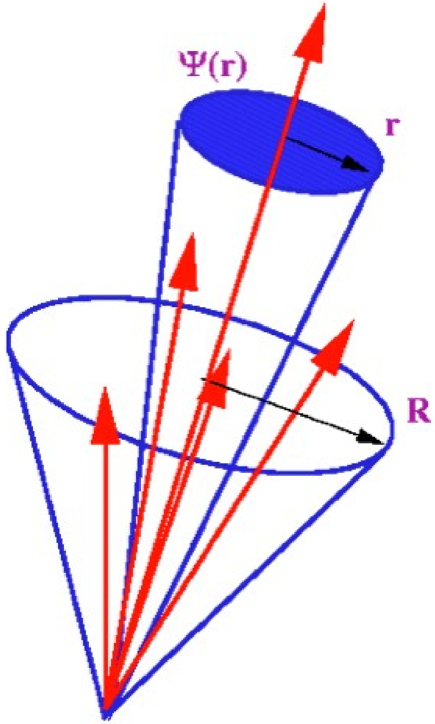
- R-parity conservation prevents massive SUSY resonances decaying exclusively to hadron or lepton jets.
- Use of boosted techniques important for reconstructing massive SM particles in SUSY cascade decays.
  - Possible Higgs discovery channels.
- In RPV scenarios SUSY resonances can be reconstructed
  - Watch out for inducing signal shapes in backgrounds.
  - Clever use of algorithms & cuts gives predictable background behaviour.

Back-ups

Are MC generator jets realistic?

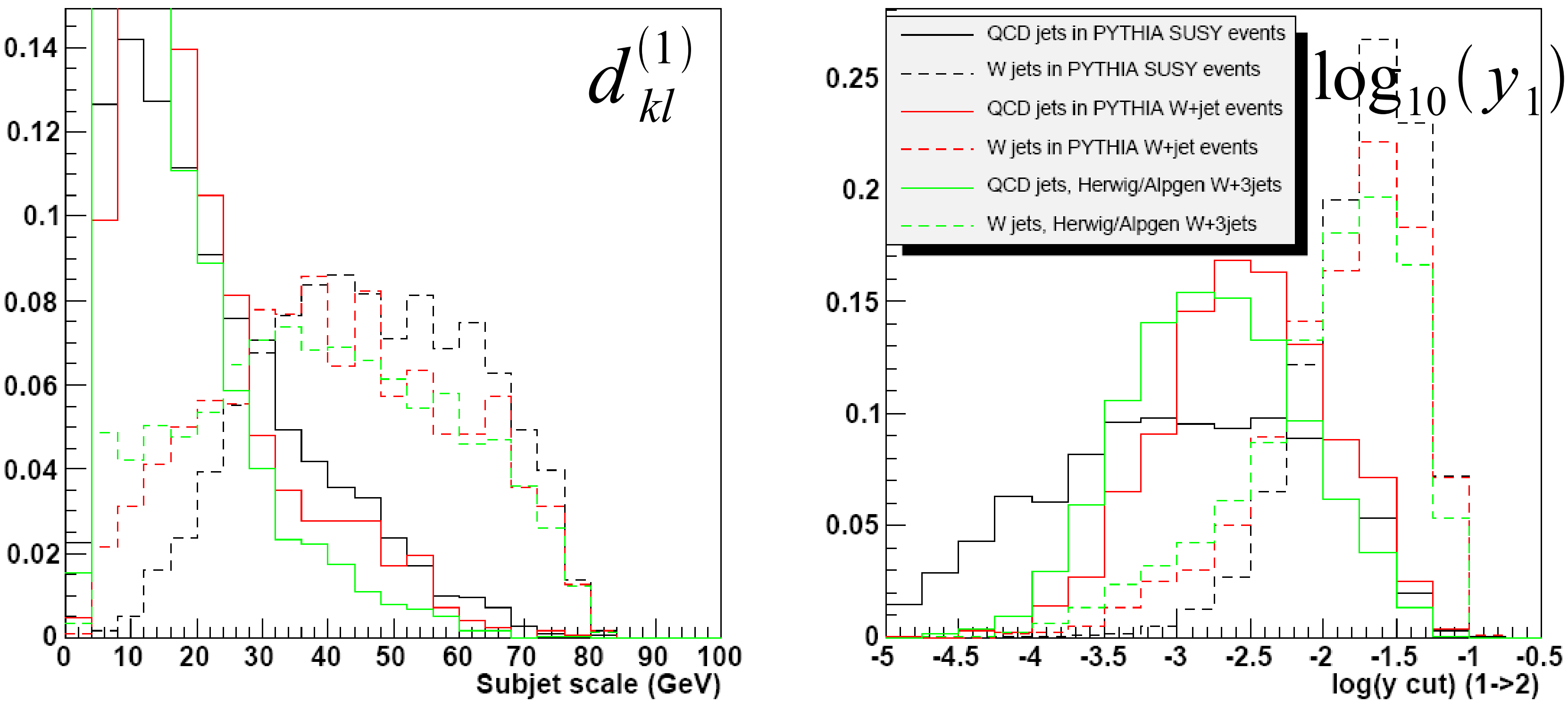


Jet shape:



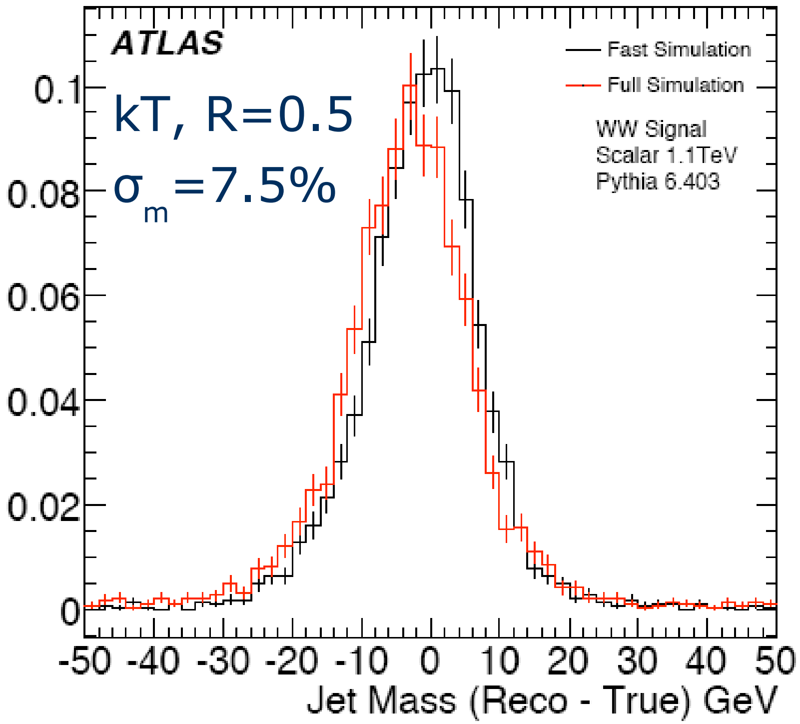
[CDF, hep-ex/0505013]

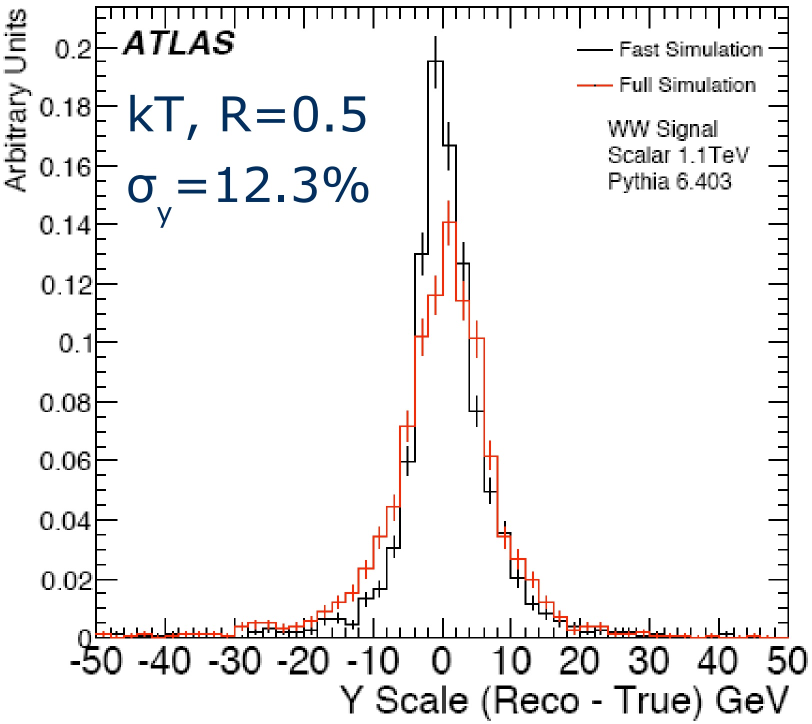
Subjet separation scale



[Butterworth, Ellis, ARR, hep-ph/0702150]

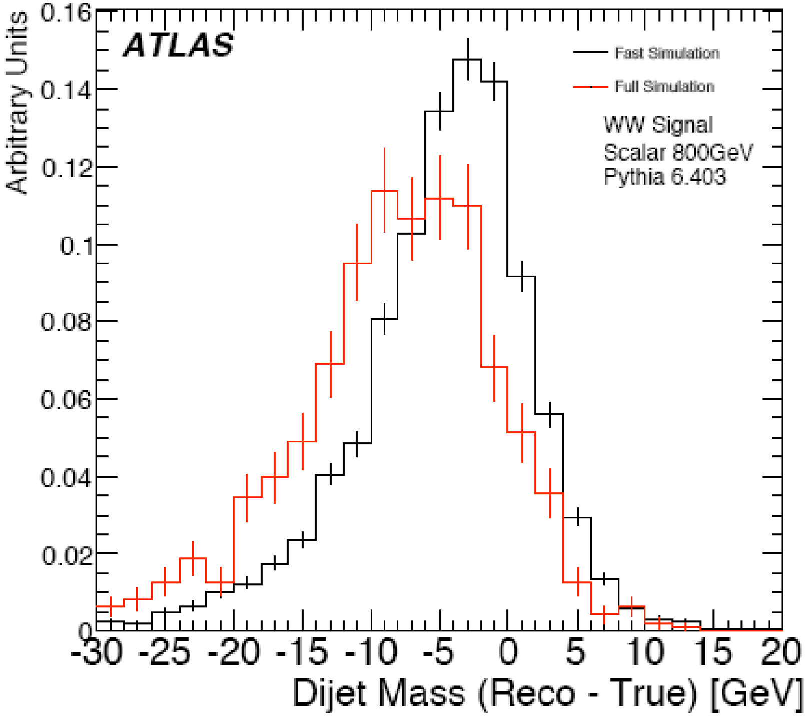
Detector resolution

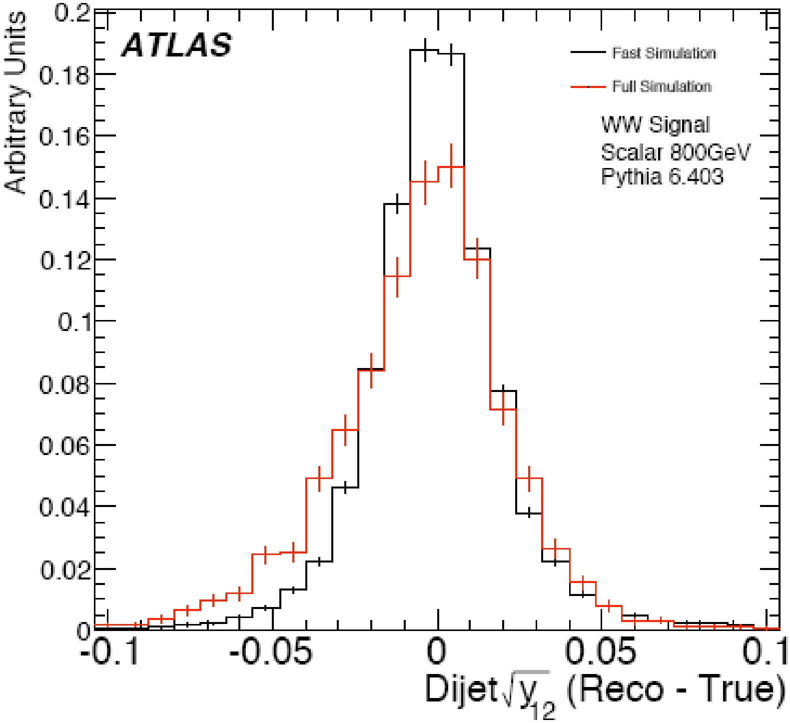




[ATLAS, arXiv:0901.0512]

Using di-jets



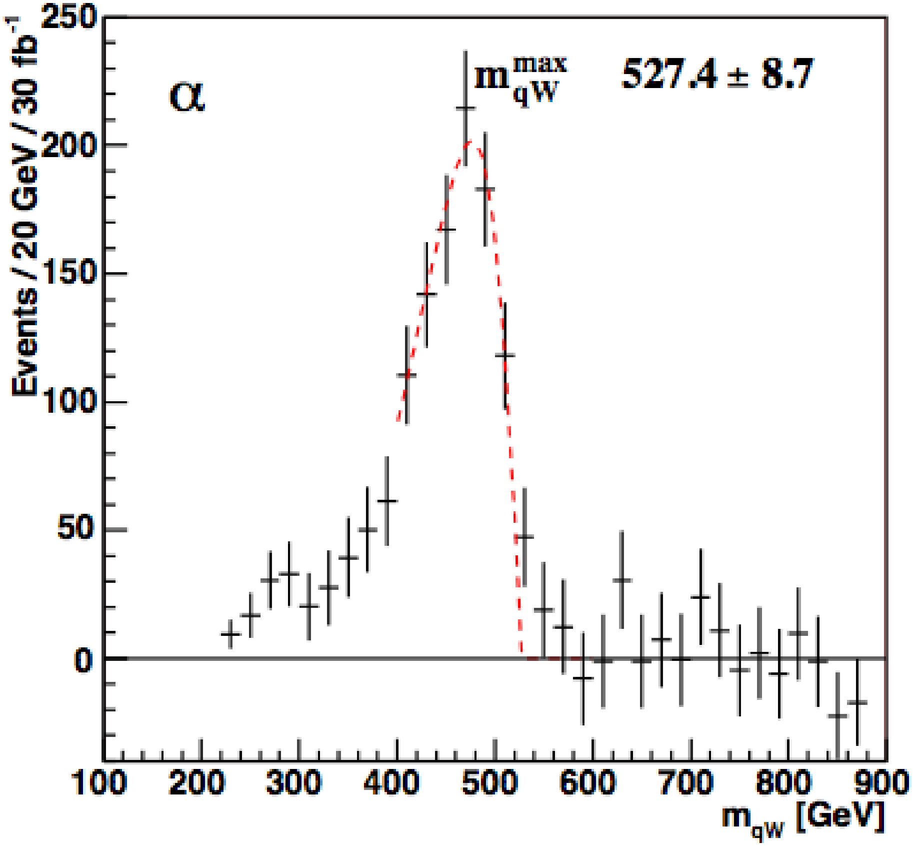


[ATLAS, arXiv:0901.0512]

Cascade decays: SM backgrounds

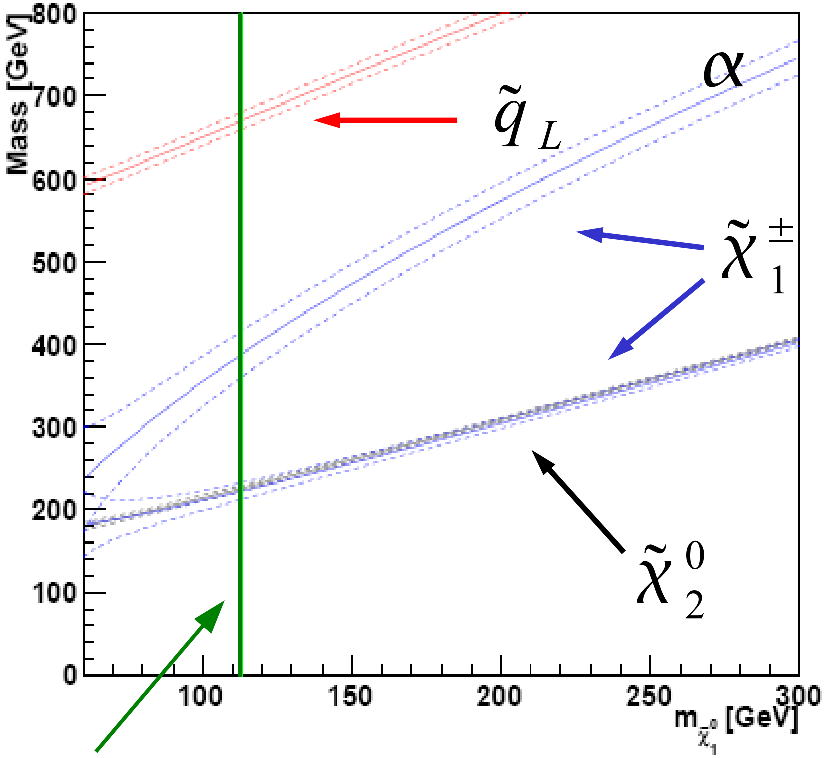
Sample	$N_{\text{generated}}$	$\mathcal{L}$ [fb^{-1}]	$N_{\text{pass}}(\alpha-\gamma)$	$N_{\text{pass}}(\delta)$
$t\bar{t}$			256.7	1287.0
50-150	26,500,000	93.0		
150-250	10,000,000	95.6		
250-400	3,500,000	120.0		
400-600	500,000	129.6		
600-	500,000	902.4		
Wj			5.2	34.5
50-150	1,100,000	0.1		
150-250	1,100,000	2.9		
250-400	1,100,000	20.2		
400-600	1,100,000	154.3		
600-	600,000	507.2		
Zj			3.2	3.0
50-150	100,000	0.0		
150-250	100,000	0.6		
250-400	100,000	4.3		
400-600	100,000	32.7		
600-	100,000	199.7		
Wjj	157,800	114.5	49.2	450.5
Zjj	112,000	99.9	43.9	417.7
$Wjjj$	50,300	227.9	127.8	1109.4
$Zjjj$	27,300	156.6	194.4	1782.9
$WW/WZ/ZZ$			9.6	95.3
50-150	100,000	1.8		
150-250	100,000	29.2		
250-400	100,000	158.2		
400-600	100,000	945.2		
600-	10,000	437.0		
WWj	201,200	100.7	9.8	98.3
WZj	162,400	90.2	0.0	0.0
ZZj	69,500	426.5	2.3	17.6
$WWjj$	107,300	98.7	23.4	215.8
$WZjj$	179,000	248.4	55.2	455.5
$ZZjj$	18,900	167.0	5.9	59.3

Cascade decays: finding edges



Subtract backgrounds using sidebands. Fit to Gaussian smeared edge.

Cascade decays: mass results



Nominal LSP mass

Using both decay chains

$$\tilde{q}_L \to q' \tilde{\chi}_1^{\pm} \to q' W^{\pm} \tilde{\chi}_1^0$$

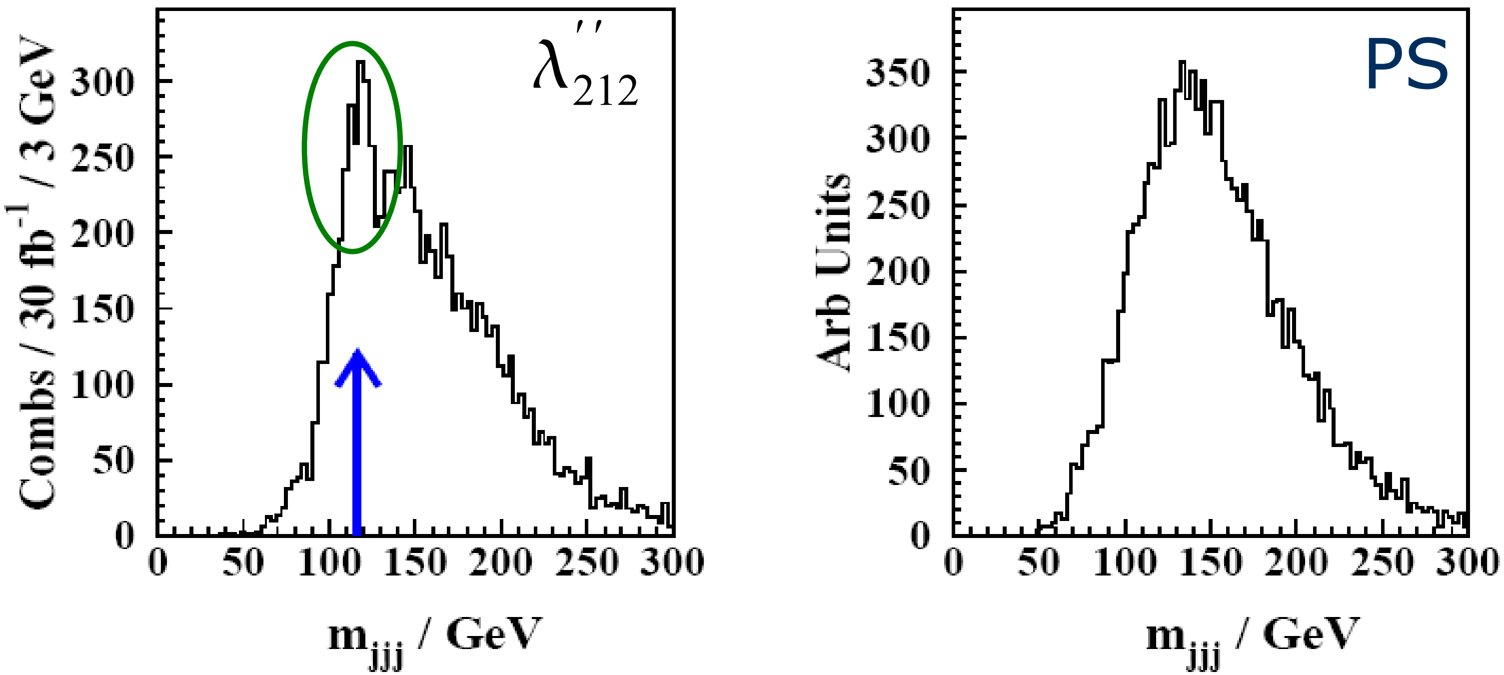
$$\tilde{q}_L \to q \tilde{\chi}_2^0 \to q Z \tilde{\chi}_1^0$$

we get strong correlations between masses from measuring edges.

Error bands from 1σ statistical errors on edge determination.

[Butterworth, Ellis, ARR, hep-ph/0702150]

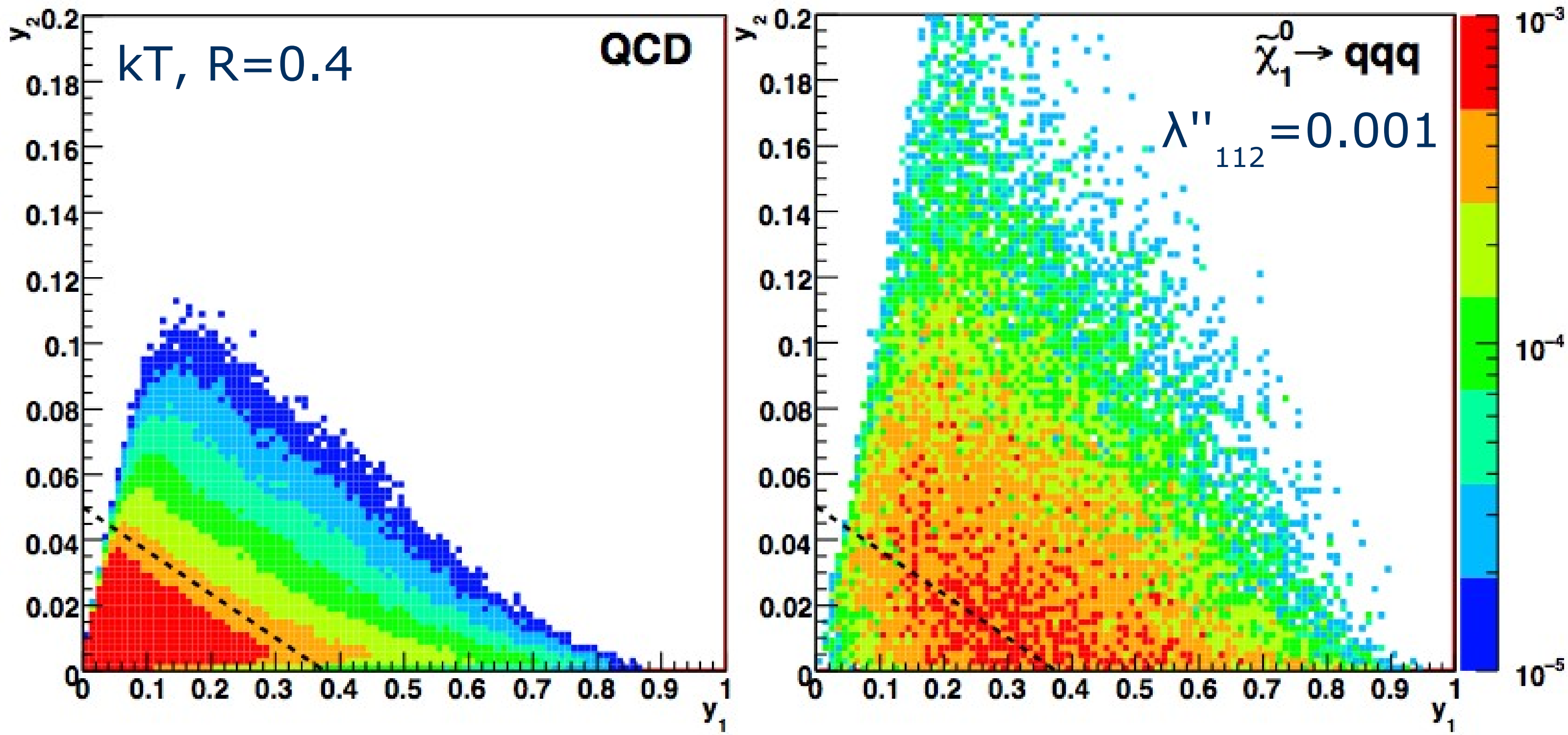
RPV decays: the classic literature



Require two leptons with $p_T > 15$ GeV.

[Allanach et al., hep-ph/0102173]

RPV decays: attempt with k_T algorithm



[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

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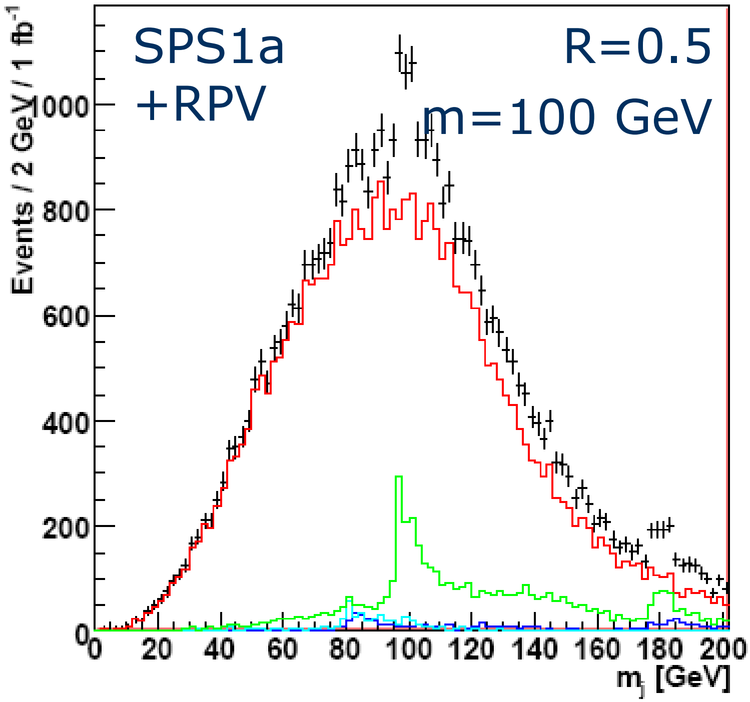


Problem: y_1-cut suppresses background, but shapes it to look like signal.

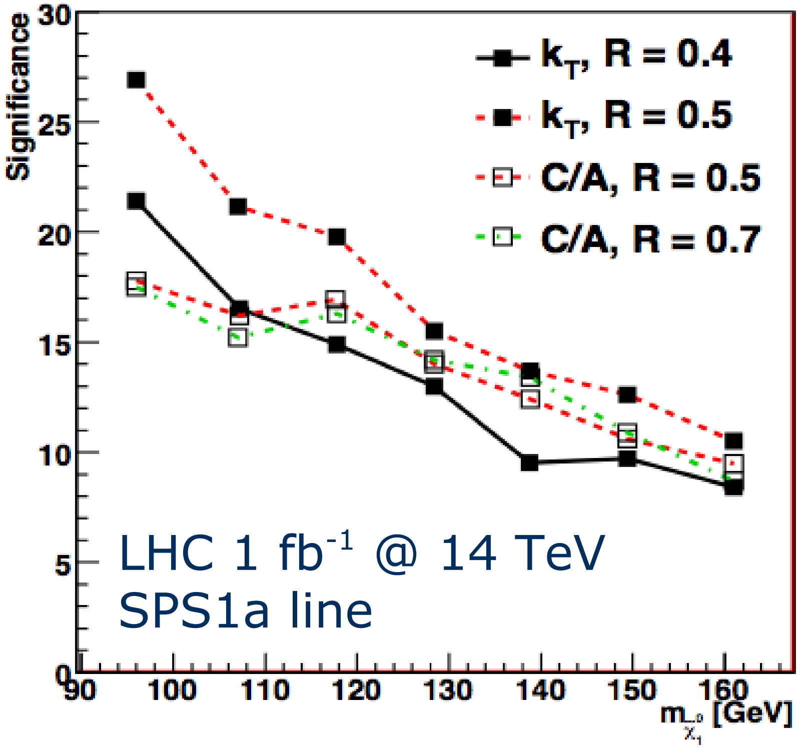
$$y_1 = \min(p_{Tk}^2, p_{Tl}^2)/p_T^2 \times \Delta R_{kl}^2/R^2$$

Some help in lowering R. However, you start to loose signal when

$$R < \frac{2m_j}{p_T}$$

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

RPV decays: overall performance



Mass determination seems limited by ATLAS/CMS jet mass resolution (~8 GeV).

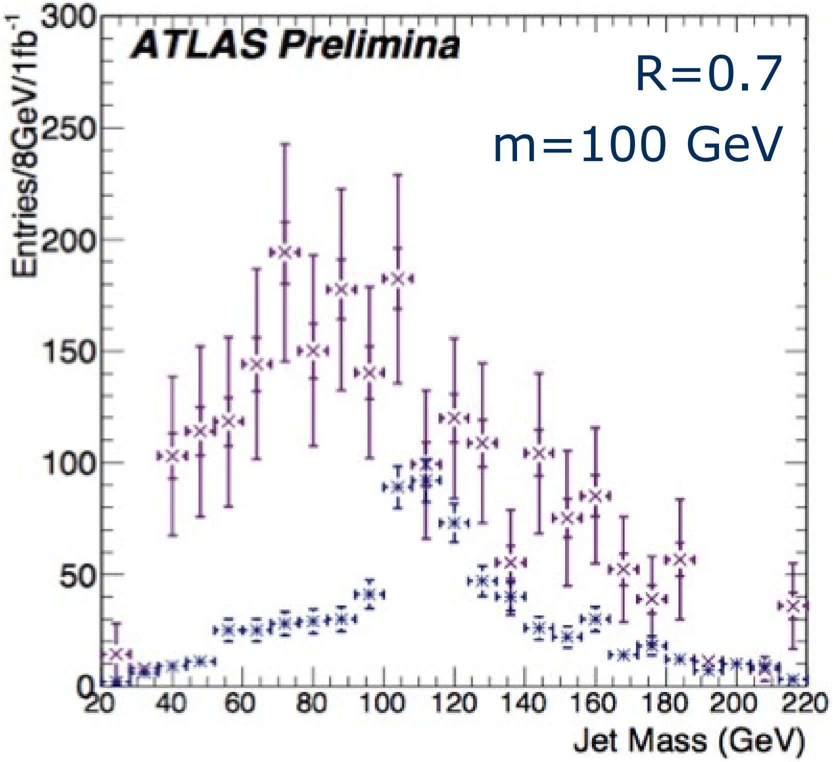
Combining neutralino candidate with extra hard jet gives squark mass estimate.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

ATLAS full detector simulation with k_T algorithm encouraging.

[French *et al.*, ATL-COM-PHYS-2009-272]

RPV decays: full simulation in ATLAS

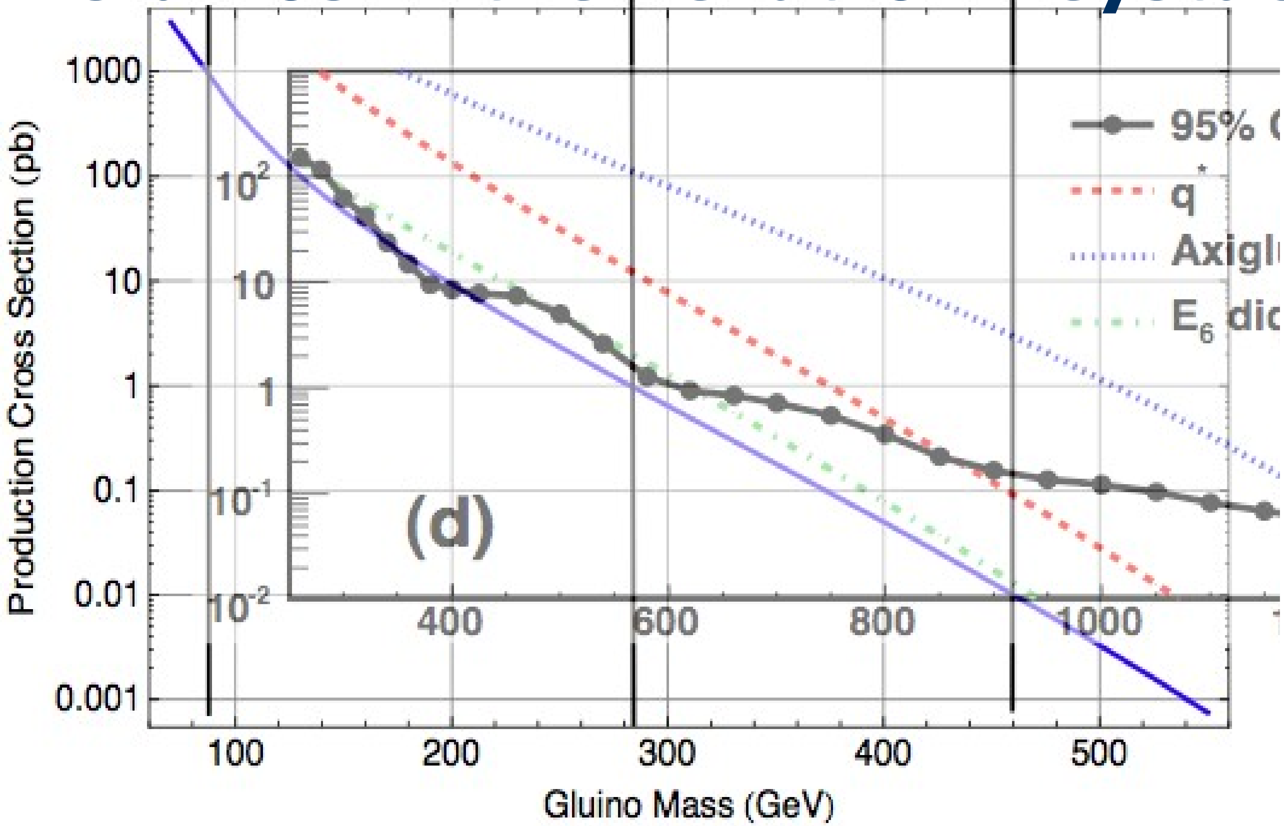


Full detector simulation on identical benchmark points with k_T algorithm encouraging.

Large error bars on QCD background, but this will not be a problem with data (see small error bars for indication).

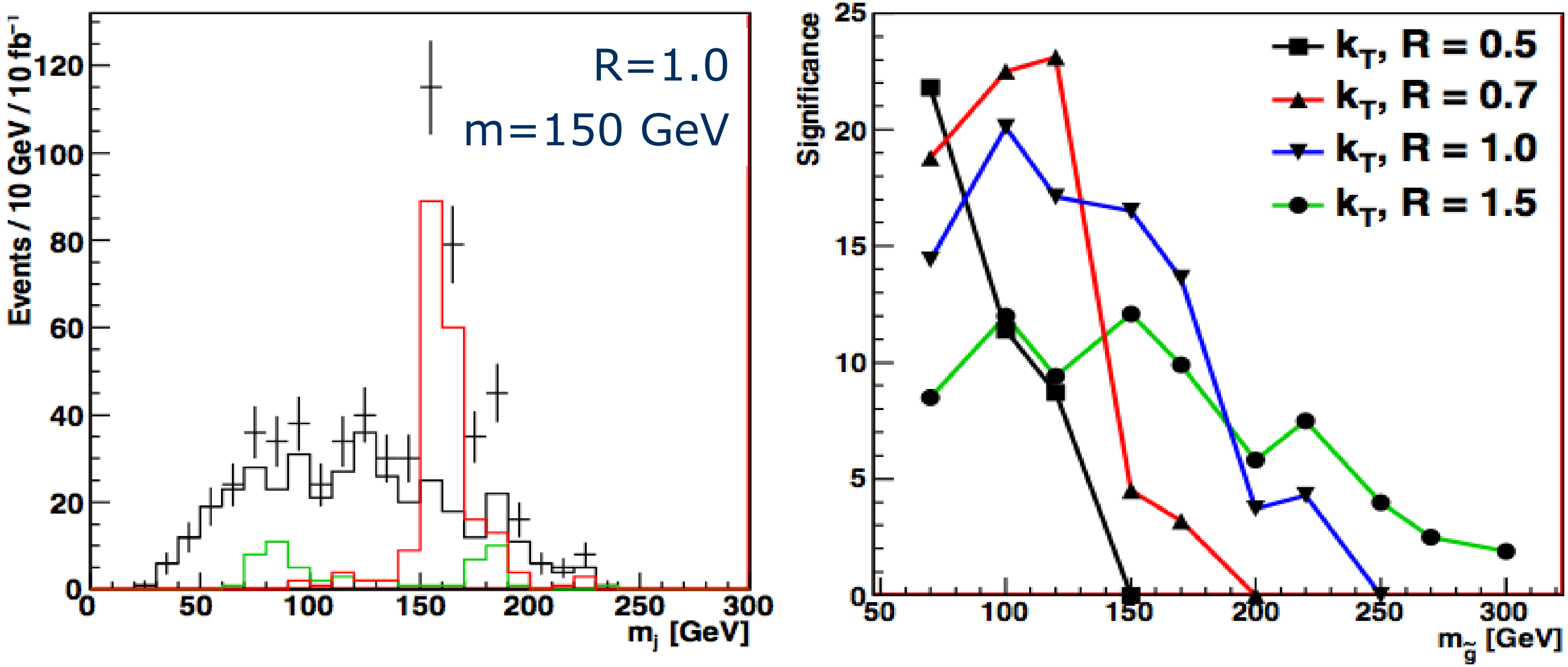
[French *et al.*, ATL-COM-PHYS-2009-272]

Gluinos in the Tevatron heystack



[CDF Collaboration, arXiv:0812.4036]

Finding gluinos with k_T algorithm



[ARR, Salam, Wacker, arXiv:1005.1229]